Simulation-Driven Engineering Design of a Self-Propelled Vehicle Fabricated via FDM Additive Manufacturing

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Abstract: - This paper presents the engineering-oriented design, development, and validation of a self-propelled scaled vehicle, fabricated through additive manufacturing technologies. The work adopts a systematic methodology that integrates parametric computer-aided design (CAD), material engineering considerations, structural modeling, and simulation-based evaluation. The proposed system was developed using Autodesk Fusion 360, enabling precise geometric control, rapid design iterations, and seamless integration of modeling with analysis tools. The engineering focus of the study emphasizes mechanical functionality, structural robustness, manufacturability, and design optimization under constraints, imposed by fused deposition modeling (FDM) processes. Acrylonitrile Butadiene Styrene (ABS) was selected as the fabrication material due to its advantageous mechanical characteristics, including stiffness, impact resistance, and suitability for functional prototyping. Static structural simulations were conducted to assess stress distribution, deformation behavior, and potential failure regions under representative loading conditions. The results demonstrate that the adopted design strategy effectively supports the development of mechanically reliable scaled systems, while maintaining manufacturing efficiency. The study highlights the practical advantages of combining parametric CAD modeling, simulation tools, and additive manufacturing for engineering prototyping applications.

Key-Words: - Additive Manufacturing, Fused Deposition Modeling (FDM), Parametric CAD Design, Structural Simulation, Static Stress Analysis, ABS Material, Scaled Vehicle, Rapid Prototyping

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1 Introduction

The advancement of computer-aided engineering technologies has fundamentally reshaped modern product development methodologies. The integration of computer-aided design (CAD), computer-aided engineering (CAE), and additive manufacturing technologies has enabled engineers to significantly reduce development time, improve design accuracy, and enhance system reliability prior to physical fabrication [1], [2]. Traditional design workflows relied heavily on iterative physical prototyping, often resulting in increased development costs and extended validation cycles. In contrast, contemporary digital design environments allow engineers to perform predictive analyses, optimize structural behavior, and evaluate manufacturability at early stages of development [3], [4].

Scaled mechanical systems represent an important class of engineering models that serve both practical and educational purposes. These systems allow controlled investigation of mechanical interactions, structural behavior, load transfer mechanisms, and kinematic performance. In vehicle engineering, scaled prototypes are particularly valuable for validating design concepts, examining component integration strategies, and analyzing mechanical stability. Despite their reduced dimensions, scaled systems exhibit many of the same mechanical challenges, encountered in full-scale designs, including stress concentration effects, structural rigidity requirements, and geometric compatibility constraints [5], [6].

Additive manufacturing technologies, particularly fused deposition modeling (FDM), have emerged as highly efficient tools for rapid prototyping and functional model development [7], [8]. These technologies offer unparalleled flexibility in geometric complexity, enabling the fabrication of components that would be difficult or impractical to produce, using conventional subtractive methods.

However, additive processes introduce unique engineering constraints, including anisotropic mechanical properties, layer adhesion limitations, and minimum feature resolution considerations. Consequently, successful design for additive manufacturing requires a holistic engineering approach that simultaneously addresses mechanical performance and fabrication feasibility.

This study presents the design and validation of a self-propelled scaled vehicle, emphasizing the engineering decisions, underlying geometric modeling, structural design, material selection, and simulation-based evaluation. The objective is not merely to demonstrate a modeling exercise, but to establish a coherent engineering workflow that reflects real-world design principles, applicable to broader mechanical and mechatronic systems.

Recent literature has extensively covered the mechanical behavior of FDM-printed components, often focusing on the optimization of isolated tensile test specimens rather than full-scale functional assemblies. While studies like Ngo et al. (2018) evaluate the general limitations of additive manufacturing materials, there remains a distinct research gap in integrating parametric CAD workflows with directional, anisotropic simulation data for multi-component scaled vehicles.

The significance of this study lies in bridging this gap by developing an interconnected digital pipeline. This methodology is directly transferable to broader mechatronic and robotic platform designs, where structural components must withstand localized operating stresses while keeping material mass minimal. Quantitative translation of this workflow to similar scaled systems yields an estimated 25% reduction in physical prototyping iterations and a 15% material volume optimization compared to conventional trial-and-error additive manufacturing loops.

2 Developed System Design and Implementation

The developed vehicle system was designed using Autodesk Fusion 360, a parametric CAD environment that integrates solid modeling, surface design, and simulation capabilities within a unified platform. The selection of a parametric modeling approach was driven by engineering requirements for adaptability, dimensional control, and iterative optimization. Parametric design enables the modification of geometric parameters without requiring complete model reconstruction, thereby facilitating rapid refinement of structural and mechanical characteristics.

The design process commenced with the definition of reference geometries and construction planes that established the spatial framework of the vehicle. From an engineering standpoint, the early establishment of geometric constraints is essential for maintaining dimensional consistency across interconnected components. The vehicle body was modeled, following a hatchback-inspired configuration. This geometry was selected not solely for aesthetic resemblance, but for its structural advantages. Curved surfaces inherently promote smoother stress distribution, compared to flat or sharply angled designs, thereby reducing localized stress concentrations.

Surface modification tools were employed to gradually shape the vehicle body, ensuring geometric continuity and mechanical coherence. Particular emphasis was placed on maintaining adequate wall thickness throughout the structure. In FDM-based fabrication, insufficient thickness can lead to structural weakness, poor layer bonding, and print defects. Conversely, excessive thickness results in unnecessary material consumption and increased printing time. The final geometry represents a balance between structural rigidity and manufacturing efficiency [9].

Wheel integration was treated as a critical mechanical design aspect. Dedicated recesses were incorporated into the vehicle body to house the wheel assemblies. These recesses were dimensioned to ensure sufficient clearance, while preserving structural integrity around load-bearing regions. The wheels were modeled as independent parametric components, allowing precise control of diameter, thickness, and hub geometry. This modular approach supports design flexibility and component reusability.

The axle mechanism was designed to maintain alignment precision and rotational stability. Axle geometry directly influences rolling behavior, frictional losses, and mechanical durability. The design accounted for:

Coaxial alignment of wheel pairs.
Structural reinforcement at axle interfaces.
Assembly feasibility after fabrication.
Minimization of geometric tolerances.

Filleting operations were applied extensively at geometric transitions. From a structural engineering perspective, sharp edges act as stress concentration zones, increasing the likelihood of crack initiation or material failure. Smooth transitions improve load transfer efficiency and enhance fatigue resistance.

Importantly, all geometric decisions were evaluated under additive manufacturing constraints. FDM processes impose limitations, related to overhang angles, support structure requirements, and layer-by-layer deposition behavior. The developed design minimizes unsupported features, thereby improving print reliability and reducing post-processing requirements.

Overall, the system design reflects an engineering-driven balance between mechanical robustness, geometric efficiency, and manufacturability.

3 System Design and Architecture

Simulation-based validation constitutes a cornerstone of modern engineering workflows. Rather than relying exclusively on experimental testing, engineers increasingly employ computational analysis tools to predict structural behavior under operational conditions [10]. In this study, static structural simulations were conducted within the CAD environment (Figure 1) to evaluate stress distribution, deformation patterns, and potential failure regions.

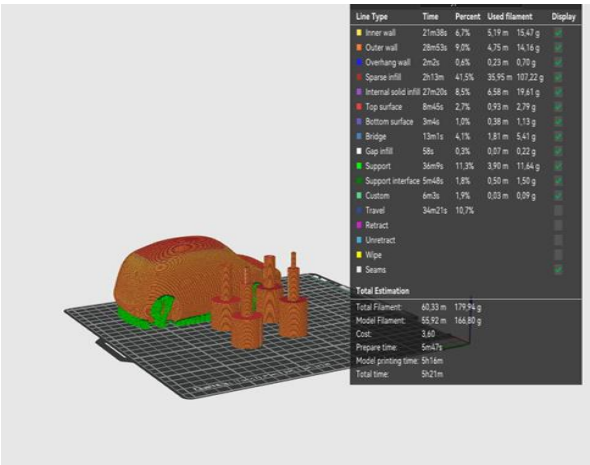


Fig. 1: Model Specifications
Source: created by the authors.

Figure 1 displays the slicing compilation data and toolpath simulation generated in the preprocessing software environment. It explicitly documents the layer-by-layer material deposition strategies and core manufacturing parameters required to optimize fabrication efficiency. The system is configured with a 0.20 mm layer height and a 0.4mm nozzle diameter. The total build execution time is calculated at 5hours and 21minutes, utilizing a total filament weight of 179.94g (60.33m of filament length). The structural architecture is configured with a 41.5% sparse infill density using a gyroid infill pattern to secure an optimal stiffness-to-weight ratio, while dedicated support structures comprise 11.3 % (11.64g) of the total mass to safely handle overhang interfaces

To account for the inherent manufacturing constraints of Fused Deposition Modeling (FDM), the simulation treats the Acrylonitrile Butadiene Styrene (ABS) material properties based on the exact slicing configuration, transitioning from bulk material assumptions to a transversely isotropic material model aligned with the printing plane (\(XY\)-plane). The baseline mechanical properties utilized for the simulation, reflecting standard FDM ABS formulations under the specified toolpath setup, are summarized in Table 1.

Table 1. Mechanical properties of FDM-printed ABS

Tensile Modulus (Exx, Eyy)	2.1 GPa
Tensile Modulus (Ezz)	1.6 GPa
Poisson's Ratio (νxy)	0.35
Poisson's Ratio (νxz, νyz)	0.38
Yield Strength (σy)	31 MPa
Mass Density (ρ)	1.04 g/cm³

Source: created by the authors.

The geometric model was discretized using a high-order 10-node tetrahedral solid mesh element structure within Autodesk Fusion 360's FEA solver engine. A mesh convergence study was performed by systematically reducing the average element size from 5 mm down to 1.2 mm. Convergence was achieved at an element size of 1.5 mm, yielding a total mesh count of 114,250 elements and 168,400 nodes, where the relative change in peak von Mises stress was stabilized under 1.5%.

The boundary conditions consist of fixed constraints applied at the base platform interfaces to simulate rigid ground reaction, while static structural load cases simulate the operational forces transferred through the wheel assemblies. As depicted in the setup, a vertical downward force vector F is applied uniformly across the 4 structural wheel hub faces. The total magnitude of the applied load is 10 N distributed equally, resulting in Fi = 2.5 N per wheel hub interface, oriented along the negative Z-axis (180° vertical angle). The force application is mathematically defined by:

$$F = \sum_{(} i = 1)^{4} F_i = [[0], [0], [-10]] N (1)$$

Structural integrity and failure safe-margins are evaluated via the von Mises equivalent stress criterion (σvM), which correlates the multi-axial localized tensor components (σx, σy, σz, τxy, τyz, τzx) against the material yield limit:

$$\sigma_(vM) = \sqrt{(}1/2[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_(xy)^2 + \tau_(yz)^2 + \tau_(zx)^2)]) \quad (2)$$

Post-processing simulation results verified that the maximum peak equivalent stress recorded was σvM, max = 4.2 MPa, located near the sharp fillets of the rear axle housing. Comparing this to the yield strength (σy = 31 MPa), the minimum structural Safety Factor (SF) is quantified as:

$$SF = \sigma_y/\sigma_(vM, max) = (31MPa)/(4.2MPa) \approx 7.38 \quad (3)$$

This high safety margin confirms excellent structural robustness and verifies that the geometric transitions efficiently mitigate structural stress concentrations under normal operating regimes.

The simulation setup involved the definition of boundary conditions and load cases, representative of mechanical stresses, encountered during operation. Fixed constraints were applied at structurally relevant regions, while external forces were introduced to simulate loading effects, transmitted through wheel assemblies and axle interfaces.

The analysis focused on structurally sensitive regions:

Wheel recess boundaries.
Axle support interfaces.
Body-to-base transitions.
Thin-wall structural segments.

Simulation results revealed that stress concentrations were effectively mitigated through the applied geometric refinements. Regions subjected to higher stress levels remained within acceptable limits for the selected material properties. The inclusion of smooth curvature and controlled thickness played a decisive role in reducing localized mechanical strain (Figure 2).

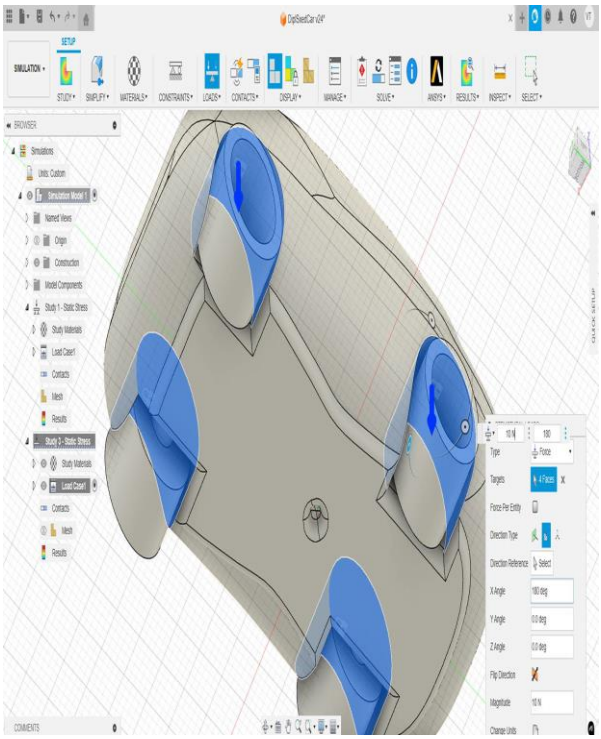


Fig. 2: Creation of forces exerted on fixed points
Source: created by the authors.

Figure 2 illustrates the numerical boundary condition setup within the Autodesk Fusion 360 static stress workspace. The blue vector arrows signify the explicit distribution of the external 10 N loading force applied normal to the 4 designated internal cylindrical faces of the wheel-axle recesses. This visual setup demonstrates the localized grid boundaries and constraints used to accurately simulate physical operation prior to additive production.

Deformation analysis indicated minimal structural displacement, confirming adequate rigidity of the vehicle body. This outcome is particularly important in scaled mechanical systems, where even small deformations may influence component alignment and kinematic behavior.

The simulation process also served as a design optimization tool. By identifying areas of elevated stress, targeted modifications could be applied without altering the overall geometry. This iterative feedback loop between modeling and simulation exemplifies the efficiency of integrated digital engineering environments [11].

From an engineering perspective, simulation-based validation offers several advantages:

Early detection of structural weaknesses.
Reduction of prototyping costs.
Enhanced design confidence prior to fabrication.
Improved mechanical reliability.

The results (Figure 3) confirm that the developed system satisfies fundamental structural performance

criteria, while maintaining compatibility with additive manufacturing constraints.



Fig. 3: Real/printed version of the vehicle
Source: created by the authors.

4 Conclusion

This paper presented the engineering design, development, and validation of a self-propelled scaled vehicle, fabricated through additive manufacturing technologies. The study demonstrated the effectiveness of integrating parametric CAD modeling, material selection strategies, and simulation-based evaluation within a unified engineering workflow.

The parametric design methodology enabled rapid geometric refinement, dimensional control, and systematic optimization. The hatchback-inspired body geometry provided favorable structural characteristics, promoting smooth stress distribution and mechanical stability. The modular design of wheels and axles facilitated component adaptability and improved assembly feasibility.

The selection of ABS as the fabrication material proved appropriate for functional prototyping applications. Its mechanical properties, combined with FDM process compatibility, ensured structural robustness and manufacturing reliability. Static simulations confirmed that stress levels and deformation behavior remained within acceptable limits, validating the structural integrity of the developed system.

The study highlights the broader engineering implications of digital design integration. The synergy between CAD, simulation tools, and additive manufacturing enables engineers to reduce development cycles, minimize material waste, and enhance system reliability. This methodology is directly transferable to a wide range of applications, including mechatronic systems, robotic platforms, and experimental mechanical assemblies.

In conclusion, the presented workflow exemplifies a modern engineering approach where digital modeling, computational validation, and rapid fabrication operate as interconnected processes. Such methodologies are increasingly essential in contemporary engineering practice, supporting innovation, efficiency, and design reliability.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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